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The plateau-insulator phase transition in the quantum Hall regime

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Abstract. We report experiments on the plateau-insulator transition in a low mobility $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}/\text{InP}$ heterostructure. An exponential law describes the resistance ρ_{xx} and we extract a critical exponent $\kappa = 0.55 \pm 0.05$ which is slightly different from the established value $\kappa = 0.425 \pm 0.04$ for the plateau transitions. Upon correction for the temperature dependence of the critical conductance σ_{xx}^* , our data indicate that the plateau-plateau and plateau-insulator transitions are in the same universality class.

Introduction

In the field of two dimensional electron gases the nature of the transitions between adjacent quantum Hall plateaus (PP transition) is an ardent topic of research. Experiments on low mobility $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}/\text{InP}$ heterostructures are a remarkable demonstration of a quantum phase transition indicating that the quantum Hall steps become infinitely sharp as the temperature T approaches absolute zero [1–2]. The maximum slope in the Hall resistance ρ_{xy} with varying magnetic field B was shown to diverge algebraically in T , $(d\rho_{xy}/dB)_{\text{max}} \sim T^{-\kappa}$, while the half width $\Delta(B)$ of the longitudinal resistance ρ_{xx} was shown to vanish like $\Delta B \sim T^{\kappa}$. In both cases the critical exponent $\kappa = 0.42$.

Due to the short-range random alloy potential scattering, the low-mobility InGaAs/InP structure shows a wide range in T for studying scaling phenomena. This is in sharp contrast to high mobility $\text{GaAs}/\text{AlGaAs}$ heterostructures where the long-range potential fluctuations dramatically complicate the observability of the critical phenomenon [3–4]. Nevertheless, the PP transitions in GaAs heterostructures have been studied extensively. In these experiments, the same value of $\kappa \approx 0.42$ was found but for a few samples only and for a small range in lowest T [4]. However, in most of the samples simple data fitting produced κ 's ranging from 0.2 up to 0.9. These results are Landau level dependent and even for a given Landau level the ρ_{xx} and ρ_{xy} data give rise to different values for κ [5].

The focus in the last few years has been on transport in the lowest Landau level. Mostly samples of lower density were used [6–7]. The resistance data look quite different from those of the other Landau levels since the transition is between a quantum Hall (plateau) phase and an insulator (PI transition).

One of the most important predictions of the renormalization theory is that the PP and PI quantum phase transitions are in the same universality class [2]. This stipulates that the same κ be observed as T approaches absolute zero. In the experiments of Refs [6–7] a comparison between the PP and PI transitions within the same sample was either not possible or not drawn. Recently, an interesting empirical result for the lowest Landau level ρ_{xx} has been reported [8]. For arbitrary samples at finite T , the ρ_{xx} data seems to depend linearly rather than algebraically on T , indicating that the problem is generically the same for all GaAs

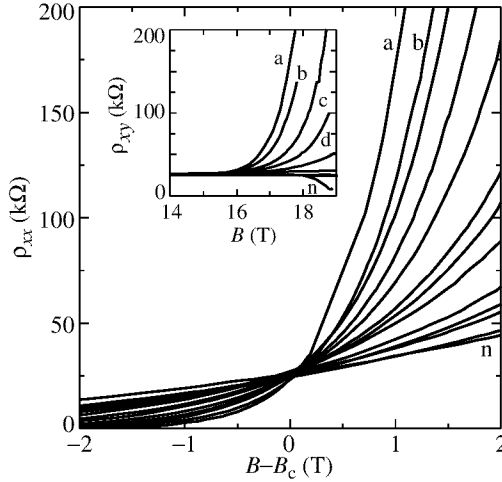


Fig. 1. Resistivity ρ_{xx} and Hall resistance ρ_{xy} (inset) versus magnetic field. B_c is the critical magnetic field defined in the text. The curves are labelled a,b,...,n and the corresponding temperatures are 0.13, 0.21, 0.26, 0.35, 0.47, 0.59, 0.83, 1.04, 1.4, 1.5, 1.9, 2.2, 3.1 and 4.2 K.

samples. Once again, the experimental design has overlooked an essential requirement for studying scaling phenomena: the importance of short-range random potential scattering — an essential prerequisite for sample choice.

1 Experimental results

We have measured the critical aspects of the PI transition and these are compared with the PP transition measured on the same sample. We benefit from the fact that our sample has been studied before [9]. In particular, the exponent κ for the PP transitions was found to be 0.42 and 0.20 for spin polarized and spin degenerate Landau levels respectively. The mobility of the sample was $\mu \approx 16000 \text{ cm}^2/\text{Vs}$ at $T = 4.2 \text{ K}$. The electron density is $2.2 \times 10^{11} \text{ cm}^{-2}$ which means that the PI transition occurs at $B \approx 16 \text{ T}$.

The experiments were carried out in a Bitter magnet ($B = 20 \text{ T}$) using a plastic dilution refrigerator (0.1–2 K) and a bath cryostat (1.5–4.2 K). The magneto transport properties were measured with a standard ac-technique with a frequency of 6 Hz and an excitation current of 5 nA. The main experimental results are presented in Fig. 1 where the resistivity ρ_{xx} and Hall resistance ρ_{xy} (inset) are plotted versus magnetic field. The ρ_{xx} data is plotted as function of $B - B_c$, where B_c separates the insulating phase at high B and the quantum Hall phase at lower B . The maximum value of the conductivity, the critical conductivity σ_{xx}^* , defines the critical field B_c .

The ρ_{xy} is at low T clearly not quantised through the metal-insulator transition. Theoretically the expectation is that ρ_{xy} is quantised through the transition. The divergence of the Hall resistance means that it is not a Hall insulator according to the definition of Kivelson et al. [10].

From the ρ_{xx} and σ_{xy} data the critical exponent can be extracted in a similar fashion as was done previously for the ρ_{xx} and ρ_{xy} data for the PP transitions [1]. For the T dependence of the σ_{xx} peak width, we obtain $\Delta B \sim T^\kappa$, with an exponent $\kappa = 0.465 \pm 0.05$. For the T dependence of the Hall conductivity is found, $(d\sigma_{xy}/dB)_{\min} \sim T^{-\kappa}$ with $\kappa = 0.435 \pm 0.05$. In the inset of Fig. 2 the width ΔB versus T is plotted for the PI as well as

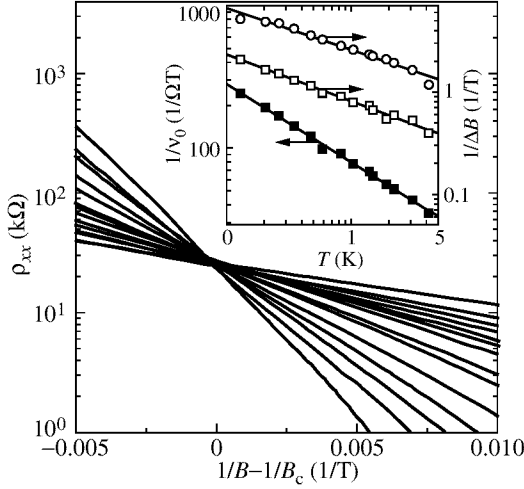


Fig. 2. ρ_{xx} data on a logarithmic scale versus inverse magnetic field. The labels and temperatures are the same as in Fig. 1. Inset: Left axis: $1/\nu_0$ vs T for the $1 \rightarrow 0$ PI transition (full squares, $\kappa' = 0.55$). Right axis: $1/\Delta B$ vs T for the $2 \rightarrow 1$ plateau transition (open circles, $\kappa = 0.42$) and the PI transition (open squares, $\kappa = 0.46$).

the PP ($2 \rightarrow 1$) transition. The latter was derived for the half width of ρ_{xx} and gave a critical exponent of $\kappa = 0.425 \pm 0.05$. The exponents $\kappa = 0.465 \pm 0.05$, 0.435 ± 0.05 and 0.425 ± 0.05 are all the same, within the experimental error, indicating that the PP and the PI transition are transitions with the same scaling behaviour.

In Fig. 2 the resistivity is plotted on a log scale as function of the difference $1/B - 1/B_c$. The resistivity can be described by the following equation:

$$\rho_{xx}(v, T) = \rho_{xx}^* \exp[-\Delta v/\nu_0(T)] \quad (1)$$

The slope (ν_0) of the straight lines around zero can be accurately determined at each T . In the inset of Fig. 2 $1/\nu_0$ is plotted versus T on a log-log scale. The data nicely follow a power law behaviour $1/\nu_0 \sim T^{-\kappa'}$ with $\kappa' = 0.555 \pm 0.05$. This value differs from the expected value $\kappa = 0.42$ by more than the experimental error. The data can not be described with a linear law $\nu_0 = \alpha T + \beta$ as proposed by Shahar *et al.* [8].

This linear dependence on T does not describe the asymptotics of the quantum phase transition at zero Kelvin. Instead it is semiclassical in nature and typically observed at finite T on samples with predominantly slowly varying potential fluctuations [3].

2 Discussion

In the next part we address the origin of the difference in exponents. The transport data of the PI transition can be accurately described by Eq. (1), where ρ_{xx}^* denotes the critical resistance. It can be written as $\rho_{xx}^* = \sigma_{xx}^*/(\sigma_{xx}^{*2} + 1/4)$. Both quantities are weakly dependent on T and this dependence is not simply irrelevant as thought previously. It turned out to be marginal and it accounts for the difference in the observed exponents, as follows:

$$\kappa = \kappa' - [d \ln(\sigma_{xx}^{*2} + 1/4)/d \ln T] \quad (2)$$

Equation (2) shows how a relatively weak T dependence in σ_{xx}^* can lead to different exponents extracted from different quantities. In Fig. 3 $1/\nu_0$ versus T on a log-log scale is

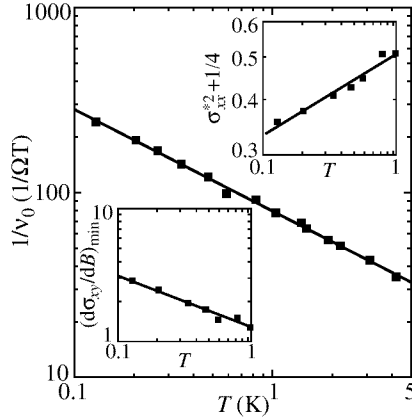


Fig. 3. $1/v_0$ vs T for the PI transition (full squares, $\kappa' = 0.55$). Upper inset: $\ln(\sigma_{xx}^{*2} + 1/4)$ vs T . The slope of the straight line equals 0.15. Lower inset: $(d\sigma_{xy}/dB)_{\min}$ vs T . The slope of the straight line equals 0.43.

replotted. The solid line gives $\kappa' = 0.55$. In the upper inset the low T data for $\ln(\sigma_{xx}^{*2} + 1/4)$ versus $\ln T$ is shown and a slope of 0.155 ± 0.03 is obtained. According to Eq. (2) $\kappa = 0.40$, which should be compared with the low T dependence of $(d\sigma_{xy}/dB)_{\min}$ (see lower inset Fig. 3).

In summary our results show that the PP and PI transition have the same scaling behaviour. We have shown that the effective exponent $\kappa' = 0.55$ of the PI transition is due to the T dependence of the critical conductance σ_{xx}^* . Weak macroscopic inhomogeneities in the sample cause the lack of universality in σ_{xx}^* . By combining the results of the PP and PI transitions we conclude that $\kappa = 0.42$ stands for the universal critical exponent of the quantum phase transition.

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